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Do We Need A Zero Pure Time Preference or the Risk of Climate Catastrophes to Justify A 2°C Global Warming Target?

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Abstract

This paper confronts the wide political support for the 2C objective of global increase in temperature, reaffirmed in Copenhagen, with the consistent set of hypotheses on which it relies. It explains why neither an almost zero pure time preference nor concerns about catastrophic damages in case of uncontrolled global warming are prerequisites for policy decisions preserving the possibility of meeting a 2C target. It rests on an optimal stochastic control model balancing the costs and benefits of climate policies resolved sequentially in order to account for the arrival of new information (the RESPONSE model). This model describes the optimal abatement pathways for 2,304 worldviews, combining hypotheses about growth rates, baseline emissions, abatement costs, pure time preference, damages, and climate sensitivity. It shows that 26 percent of the worldviews selecting the 2C target are not characterized by one of the extreme assumptions about pure time preference or climate change damages.

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Do we need a zero pure time preference or the risk of climate catastrophes to justify a 2°C global warming target?*

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1 Introduction

One of the intriguing results of the Cop 15 (Copenhagen climate change conference 2009) is the apparent contradiction between the absence of a firm commitment on country or regional targets and the confirmed 2°C objective, i.e. the stabilization of global warming below a 2°C rise in global temperature. Obviously, this target is surrounded by ambiguity about whether it is a strict ceiling or a long term objective with some degree of overshooting allowed in between. The reference to that threshold originates in a visual reflex, a 550 ppm target fitting just in the middle of the IPCC SAR figure displaying various scenarios between 350 ppm and 1000ppm. This target was also supported by the intuition that it would not lead to extreme mitigation costs, given published results from economic models of the time.

This 550 ppm target was supposed to be tight enough to keep temperature increase below two degrees above pre-industrial temperatures. But, some years later, the assessments of climate sensitivity became more pessimistic and it seems unlikely that a 550 ppm target will secure a 2°C objective and the delay in mitigation actions after the semi failure of international climate negotiations since the Kyoto Protocol makes it far more difficult to reach significantly tighter targets like 380 ppm.

But, the gap is obvious between, on the one hand, this political claim and, on the other hand, the published economic literature that relies on a cost-benefit analysis of climate policies (Tol, Mendelsohn, Nordhaus, etc.) or even the Stern report that pleads in favor of early action but does not appear to support firmly the 2°C objective.

The overwhelming majority of tenants of the 2°C target can be found in scientific and intellectual circles that reject the very idea of CBA in these matters. Some start from an ethical rejection of a full monetization of climate change damage (value of life, intrinsic value of irreplaceable assets), but many simply question the credibility of such estimates given the cascade of uncertainty between GHGs emissions and ultimate damage. In both cases, they prefer to refer to the search for "safe corridors" normatively fixed from qualitative insights provided by integrated models.

In a companion paper (Hallegatte et al., 2009), we analyze the many reasons why, beyond a 2°C temepratture increase, the uncertainty may become so high that it would generate very high adaptation costs and significant residual damage. With a temperature increase higher than 2°C, the climate system enters in a domain where the validation of climate models becomes less reliable, making their projections more uncertain. Also, the ecosystem reaction is not well understood for large warming. Finally, the difficulty in mobilizing the full capacity of adaptation potentials in case of very fast environmental change, the risks of mis-adaptation, the inertia of capital stocks, and many sources of ripple effect within the economic system make the full cost of a rapid climate change very uncertain.

This enumeration delivers a puzzling message: on one hand it gives a set of reasons why climate change damage may be high enough to economically justify the 2°C ceiling; on the other hand it explains that, given the uncertainty and the current state of scientific knowledge, no fully-fledged monetary assessment of damage can be conducted.

But the nagging economic question remains which implies to carry out some form of cost-benefit trade-off: a dollar, euro, yen or yuan spent for climate mitigation will not be spent elsewhere. The only way out (Manne and Richels, 1995; IPCC, 1996) is to reframe the cost-benefit analysis in the context of a sequential decision-making process with progressive learning and continuous reorientation of the initial course of action. Also, in the absence of robust monetary assessment of damage, a solution is to give monetary values to possible risks, through the introduction of a willingness to pay for avoiding poorly understood but potentially serious risks.

Note that this approach does not contradict the tenants of a cost-efficiency approach. Indeed the trade-off between costs and benefits of action still exists but is implicit. Essentially, the only difference between a cost-benefit analysis and a cost-efficiency analysis is the fact that overshooting is prohibited in the latter (as if the willingness to pay would reach infinity just after another marginal increase in emissions), while it is allowed in the former.

This type of approach (Ha-Duong et al., 1997; Ambrosi et al., 2003) tries and balances the sunk costs due to a premature high level of action against the environmental risks of a delay in action. The main lesson from this approach is the importance of the asymmetry between these two costs: the cost of loosening the carbon constraint in view of new and more optimistic information is relatively lower than the very high costs of either supporting the environmental irreversibility effect or accelerating mitigation policies that would have been too lax in a first stage.

Actually the issue is that there are as many cost-benefit balances as opinions about the future of the world economy and the risks triggered by global warming. These worldviews are composed of :

- conjectures about baseline economic growth and related GHG emissions;
- assessments of costs of carbon saving technologies;
- choice of the pure time preference which translates consumption flows

into utility flows, and balance the utility of present and future generations;

- beliefs on climate change damage, which in turn consist in beliefs about climate, about the ultimate level of damage, and about the shape of the damage function;
- sets of priors about probability distribution on the uncertain parameters.

We start from the idea that there is no scientific reason to close prematurely these divergences in views, some incorporating real scientific and ethical controversies. We consider it more useful to produce a set of numerical experiments on all these worldviews to elicit for which of them a 2°C objective would be economically sound.

We will do so through a stochastic optimal control model, the RESPONSE model. This model balances discounted costs and benefits of climate policies and calculates optimal response pathways (see a full description in Ambrosi et al. (2003) and in the appendix).

Using this model, we find that there are as many optimal emissions pathways and associated carbon prices as there are combinations of worldviews and assumptions. This multiplicity simply translates the current diversity of opinions. The advantage of a stochastic optimal control framework is that it captures a situation in which each club of opinion (corresponding to a specific combination of worldviews) admits (i) that there are other possible opinions on climate change; and (ii) that its own anticipation of climate change may be proven wrong after a given date. Each club attaches priors to damage assessments, even for others than its own "best guess," and it tries to always be in position to bifurcate to other targets if new information shows it to be necessary.

We can thus identify the combinations of worldviews that make a 2°C target economically sound, without resorting to arbitrary normative targets. We can then analyze the main characteristic of these combinations, in order to identify the parameters that are conducive for action. More precisely the issue is whether a 2°C objective can be justified without resorting to a very low pure time preference, like the Stern's exercise, or to the expectation of a possible global catastrophe, like in the Weitzman's exercise. On a more policy oriented approach, identifying the set of hypothesis and beliefs that are consistent with the 2°C target may be useful in future climate negotiation to discriminate between political claims and credible commitment to reach that target.

2 The model: A process of optimization under uncertainty

RESPONSE is an Integrated Assessment Model (IAM), which couples a macroeconomic optimal growth model[1] following the tradition launched by the seminal DICE model by Nordhaus (Nordhaus, 1994), with a simple climatic model. Here we present its basic equations, derived from the model used in Ambrosi et al. (2003).

The program maximizes an intertemporal social welfare function under uncertainty. Uncertainty holds on both climate sensitivity (and on temperature increase $\theta_{t,at}^{s,j}$) and damage denoted D^j. To encompass the whole range of beliefs on the true climate damage, the model considers five states of the nature s for climate sensitivity (θ_{2x}^{s} in table 2) and five states j (Z_j in table 2) for the form of damage. As climate change is basically a non-reproducible event, a subjective distribution of probabilities (p_s and q_j) is given to each state of the world (presented in table 2). These probabilities can be interpreted as the level of confidence a stakeholder attaches to each existing climate scenarios and to each assessment of climate change impacts.

The uncertainty actually operates at first period, before a point in time denoted t_{info} at which uncertainty is resolved about the genuine level of climate change damage and on the climate sensitivity. Some argue that the "climate proof" was already provided by the two last IPCC reports, the Stern Review and the long serie of climate catastrophes over the past decade. What is meant by resolution of uncertainty is that all forms of controversies are stopped, and that there is a wide consensus on the validity of information. In the forthcoming simulations the date t_{info} is set at 2050. At the end of this learning and self-convincing process, people adapt their initial behavior to new information, they accelerate abatements in case of "bad news" and relax the effort in case of "good news".

We note $S = (5, 5)$ the number of states for s and j. The intertemporal social utility function to maximize between now and the ultimate period T (here $T = 2200$) is:

$$\sum_{s,j=1}^{S} p_s q_j \sum_{t=0}^{T-1} N_t \Gamma^t u\left(\frac{C_t^{s,j}}{N_t}\right),$$

with $u(.)$ the utility function, N_t the population at t which is assumed to grow at an exogenous rate, and $C_t^{s,j}$ the consumption of a composite good at

[1] very like Ramsey-Cass-Koopmans' models (Ramsey, 1928; Koopmans, 1965; Cass, 1966)

t in the states of the world s and j. The individual discount factor Γ may be written as $\frac{1}{1+\rho}$, with ρ the pure time preference.

The following equations represent the four constraints of the problem. $\forall s$ and $\forall j$,

- capital dynamics:

$$K_{t+1}^{s,j} = (1-\delta)K_t^{s,j}+(Y(K_t^{s,j}, L_t)-C_t^{s,j}-C_a(a_t^{s,j}, a_{t-1}^{s,j}, K_t^{s,j})-D^j(\theta_{t,at}^{s,j}, K_t^{s,j})),$$

where $K_t^{s,j}$ stands for the capital at t which is set at the level $\overline{K}_t$ whatever the states of the world are, when $t \leq t_{info}$. δ is the parameter of capital depreciation. L_t is an exogeneous factor of labor which enters $Y(.)$, the traditional Cobb-Douglass function of production. Since technical inertia is a key determinant of the problem, we follow the route initiated by (Ha-Duong et al., 1997) and consider the following abatement cost function:

$$C_a(a_t^{s,j}, a_{t-1}^{s,j}, K_t^{s,j}) = PT_t\left(a_t^{s,j}\zeta + (BK-\zeta)\frac{(a_t^{s,j})^\nu}{\nu} + \frac{Y_0}{E_0}\xi^2(a_t^{s,j} - a_{t-1}^{s,j})^2\right)E_t^{s,j}$$

with $a_t^{s,j}$ the fraction of emissions' cuttings[2]. The cost function has two main components: the absolute level of abatement $\frac{(a_t^{s,j})^\nu}{\nu}$, with ν a variable power coefficient, and a path dependent function which penalizes the speed of decarbonization $(a_t^{s,j} - a_{t-1}^{s,j})$ so that it costs 1% of annual GDP to totally decarbonize the economy in 50 years, whereas it costs 25% of annual GDP if total abatement is achieved within 10 years. Then, PT_t is a parameter of exogenous technical progress, BK stands for the current price of backstop technology, ζ and ξ are fixed parameters, and $E_t^{s,j}$ represents the level of emissions. Emissions are considered here as a fatal product and can be written as:

$$E_t^{s,j} = \sigma_t Y(K_t^{s,j}, L_t),$$

with σ_t the carbon intensity of production which declines progressively thanks to technical progress ($\sigma_0 = E_0/Y_0$).

Finally $D^j(\theta_{t,at}^{s,j}, K_t^{s,j})$ denotes damage induced by $\theta_{t,at}^{s,j}$, the temperature increase due to GHG emissions from preindustrial period to the date

[2] If $a_t^{s,j} = 1$, then emissions become nul; on the contrary, if $a_t^{s,j} = 0$, then no effort of abatement is provided

t. Rather than traditional power functions, we use sigmoidal functions (Ambrosi et al., 2003) to represent non linearity effects in damage (see the appendix for the mathematical formulation of the function). Within capital dynamics, damages amputate a part of the production which has to be shared between consumption, abatement and investment.

- temperature dynamics:

$$\theta_{t,at}^{s,j} = F(E_t^{s,j}, E_{t-1}^{s,j}, ..., E_{t_{info}+1}^{s,j}, \overline{E}_{t_{info}} ..., \overline{E}_0).$$

  This equation links temperature increase at time t to past carbon emissions flows E_t, E_{t-1} up to $\overline{E}_0$[3]. This function incorporates the linear three-reservoir model of carbon cycle by Nordhaus (Nordhaus and Boyer, 1999) and a temperature model very close to Schneider and Thompson's two-box model (Schneider and Thompson, 1981) (see the appendix for a detailed presentation of carbon and temperature dynamics).

3 Worldviews and scenarios

Each scenario is based upon a set of beliefs on six key and controversial parameters: economic growth, the speed of the autonomous decarbonization of the production system, technical costs of GHG emissions' cuts, the weight given to future generations, the magnitude of climate damage and finally the index of climate sensitivity.

To span the array of scientific opinions, we retained 9 combinations for the climate damage and the climate sensitivity (see table 2). For the economic and technological parameters, the extreme values given by the last IPCC report are considered (IPCC, 2007b,a) (see table 1)[4], and four values uniformly distributed within these bounds are used to cover the range of scientific uncertainty.

3.1 Economic and technological parameters

In the baseline scenario (i.e. when climate change is not considered), economic growth is, on average over the whole twenty-first century, in the range [1.45%,

[3]Notice that before t_{info}, as abatement is set whatever the states of the world are, emissions flows are also set

[4]Note that, regarding abatement costs, the critic of Pielke et al. (2008) et al in Nature concerns the figures published in the synthesis report. We retained here the "primary material" of the report that includes both optimistic and pessimistic cost assumptions

Sensitive variables	Parameters of the model	lower value	upper value
Economic growth	$\frac{ln(Y_t/Y_0)}{t}$	$1.45\%.year^{-1}$	$3\%.year^{-1}$
Emissions	Parameter of decarbonization ψ_0	0.5%/year	1.5%/year
Abatement costs	BK_{2008}, ν, ζ, α	110\$/t CO_2, 3, 0, 1%	1023\$/t CO_2, 4, 15, 1.35%
Ethical preferences on future	Pure time preference ρ	0.1%	2%

Table 1: Value ranges for the socio-economic scenarios

3%], with higher growth rates over the decades. Its impact on the volume of carbon emissions is determined by the carbon intensity σ_t which in turn is driven by ψ_t which captures the joint impact of technical change and fossil resources depletion: $\sigma_t = \sigma_0 e^{-\psi_t t}$ with $\psi_t > 0$. For a given population level, carbon emissions level is proportional to $E_0 e^{(g-\psi_t)t}$. As long as $g > \psi_t$ (with ψ_t set at its initial level), carbon emissions would remain strictly growing with time for most (ψ_0, g) couples. To guarantee that emissions decrease by the end of the century, as predicted by the overwhelming majority of available scenarios, ψ_t progressively increases so that it can become higher than g:

$$\psi_t = \psi_0 e^{\beta t} + 1.1g(1 - e^{\beta t}),$$

with $\beta > 0$, the speed of growth of ψ_t. Thus,

$$\sigma_t = \sigma_0 e^{(\psi_0 e^{-\beta t} + 1.1g(1-e^{-\beta t}))t}.$$

Beliefs about mitigation costs are captured through the price of the backstop carbon free technology BK_{2008} capable to achieve total abatement of CO_2 emissions. This technology is supposed to be available at each time period, with a cost declining over time, but it penetrates only when it becomes cost-efficient at a rate function of the rate of capital turnover. Costs of backstops are not explicitly mentioned by the last IPCC report but can be determined in order to fit with its published cost data (Figure 3.25 page 205). We retained an initial range of [110\$/tCO_2, 1023\$/tCO_2] and decreases at a rate of 1% and 1.35% for optimistic and pessimistic opinions respectively.

As regards to pure time preference ρ, it is not the place to close the dispute between the advocates of normative choice of that parameter and the advocates of a positive approach consistent with observed behaviors and virulent ethical controversies rooted in old intellectual traditions (Ramsey (1928)

Types of beliefs	Optimistic	Moderate	Pessimistic
Temperature thresholds of damage triggering (in °C)	$Z^1 = 2,\ Z^2 = 2.5,\ Z^3 = 3,\ Z^4 = 3.5,\ Z^5 = 4$		
Distributions of probabilities	$q_1 = 0.02$ $q_2 = 0.03$ $q_3 = 0.1$ $q_4 = 0.3$ $q_5 = 0.55$	$q_1 = 0.1$ $q_2 = 0.25$ $q_3 = 0.3$ $q_4 = 0.25$ $q_5 = 0.1$	$q_1 = 0.55$ $q_2 = 0.3$ $q_3 = 0.1$ $q_4 = 0.03$ $q_5 = 0.02$
Expected damage for 2°C increase of mean temperatures	0.8% of GDP	2% of GDP	3.2% of GDP
Values of climate sensitivity (in °C)	$\theta_{2x}^1 = 1.5,\ \theta_{2x}^2 = 2.3,\ \theta_{2x}^3 = 3,\ \theta_{2x}^4 = 3.8,\ \theta_{2x}^5 = 4.5$		
Distributions of probabilities	$p_1 = 0.55$ $p_2 = 0.3$ $p_3 = 0.1$ $p_4 = 0.03$ $p_5 = 0.02$	$p_1 = 0.1$ $p_2 = 0.25$ $p_3 = 0.3$ $p_4 = 0.25$ $p_5 = 0.1$	$p_1 = 0.02$ $p_2 = 0.03$ $p_3 = 0.1$ $p_4 = 0.3$ $p_5 = 0.55$
Expected beliefs on the value of climate sensitivity	2.5°C	3.25°C	4°C

Table 2: Table of all scenarios of potential damage

vs Koopmans et al. (1964)). This is why we retained, as two extreme values of $\rho = 0.1$ as recommended by N. Stern (Stern, 2006) and 2% (Weitzman, 2007b).

The combination of values in table 1 gives $4^4 = 256$ scenarios.

3.2 Climate change damage

Table 2 show the values retained for climate sensitivity and the threshold of temperature increase which triggers non linear damage. We consider five possible levels for climate sensitivity θ_{2x} (1.5°C, 2.3°C, 3°C, 3.8°C and 4.5°C) and damage are described through a hybrid linear-sigmoidal function rather than a power function to capture the possible emergence of non linear damage (Ambrosi et al., 2003). We consider 5 possible levels of thresholds of temperature increase Z (2°C, 2.5°C, 3°C, 3.5°C and 4°C), beyond which catastrophic events, in the Weitzman's sense (Weitzman, 2007a) cannot be excluded. Notice that the overshooting of those thresholds does not suddenly triggers its total effect (6% of GDP loss); damage spread out progressively over a temperature range η which corresponds to an arbitrary additional 0.6°C (for instance, over the range [1.7°C, 2.3°C] for the lowest possible threshold).

For each parameter, three opinions are represented, each of them defined by a specific distribution of probabilities on the different possible values of the two uncertain parameters. Optimistic (or, pessimistic) belief on the threshold is consistent with a probability distribution which put a great weight to the highest (respectively, the lowest) value of the threshold (4°C or respectively, 2°C) and a declining weight to other levels of the threshold. In the same way, optimistic (or, pessimistic) beliefs on climate sensitivity are translated by a probability distribution which put a great weight to its lowest (respectively, its highest) value (1.5°C or respectively, 4.5°C).

Combining the numerical assumptions displayed in table 2 gives $3^2 = 9$ climate damage scenarios. Eventually, combining them with the 256 economic scenarios gives 2,304 integrated scenarios which cover the whole range of logically possible opinions in the climatic debate.

4 Worldviews and sets of economic rationale for a 2°C target

Simulations show that launching in 2010 GHG abatement policies aiming at a 2°C target[5], and securing the capacity to redirect the emissions trajectory in 2040, appears economically sound to 783 out of 2,304 worldviews.

This section will investigate the population that sees a 2°C target as a rational economic choice, to understand what are the beliefs that are consistent with a 2°C target and see if a 2°C target is only consistent with a very low pure time preference (like in the Stern report) or with the possibility of a catastrophic climate change (like in Weitzman's exercise).

There are many reasons that explain why a given combination of parameters results in a pro or anti 2°C choice (GDP growth, decoupling between baseline emissions and GDP, GHGs abatement costs). Table 3 focuses on two parameters because of their importance in policy debates: the pure time preference (PTP) and the assumption about the shape of the damage curve (existence of several thresholds).

[5]This choice does not guarantee that the 2°C target will be met at all point in time for all these 783 combinations. In such a cost-benefit framework, indeed, the optimal trade-off may allow for transitory overshoots (the 2°C target is met in all cases in 2200, but the temperature can exceed this value over the entire trajectory).

Impact of crossing the threshold	0.1078	0.3776	0.7679
PTP			
0.10	96	116	142
0.73	40	62	95
1.37	19	45	75
2.00	8	29	56

Table 3: Number of worldviews supporting a 2°C target as a function of PTP and of possible damage thresholds. This table shows the relative influence of the pure time preference and of the beliefs about the shape of the damage curve (i.e. the share of damage due to the crossing of uncertain thresholds relative to the total damage).

Impact of crossing the threshold	0.1078	0.3776	0.7679
PTP			
0.10	48	68	94
0.73	7	22	49
1.37	3	14	36
2.00	1	6	21

Table 4: Number of worldviews supporting a 2°C target, after removal of the most optimistic mitigation costs hypothesis.

Unsurprinsingly the major part of the pro-2°C (54%) have a Stern-type of pure time preference (Table 3). But this ethical choice does not appear as a pre-condition for a very ambitious action since a significant number of combinations (93) with a high 2% PTP result into a pro-2°C choice. Clearly most of them (60%) share the idea of strongly non linear damage curves and there are seven times more chances to find a pro-2°C attitude in this category of worldviews that amongst those who believe that the damage curve is linear.

But one can argue that these figures are biased by the fact that some of the combination lead to overwhelmingly optimistic visions of abatement costs (be for reasons of high decoupling in the baseline or because of very low costs of carbon free technologies or thanks to any combination of this type of hypothesis). Table 4 then reports the same type of information after exclusion of those "technological panglossians".

The first striking result is that there is a threshold in the effect of the PTP: for the combination in which people attribute a low importance to non-linear damage curves (with a share of non-linear damage of 0.1078). In that case indeed only 18% have a PTP higher than 0.1% (a single one configuration for a 2% PTP). This is clearly due to the fact that, with a linear damage curve, high damage occur very late, making the role of the discount rate critical in a cost-benefit analysis.

The second result is that, even after exclusion of the overly optimists about abatement costs a 2°C objective is still economically sound for a significant number of combinations with medium to high PTP (47%). This is due to a mechanism that does not appear with a linear cost-curve: with a threshold, the most pessimistic hypothesis about climate variability make these thresholds to appear sooner, triggering damage which grow faster and thus outweight, during a period, the effect of discounting.

In the club of those who believe in linear damage curve, there is 48 times more people who have a very low PTP than a 2% one; this ratio is only 4.5 for those who believe in strongly non linear damage.

If we now exclude the combinations that could be suspected of being biased in favor of action (very low PTP and very low mitigation cost) the number of pro-2°C worldviews is 159 amongst which two-thirds anticipate high non linearity in damage curves and 26.4% a medium non linearity. This remaining group is critical because it contains the sensitive (and perhaps majority) groups of opinions which are neither extremely optimistic about mitigation costs nor ready to sacrifice too much their welfare to the welfare of their descendants.

5 Conclusion

Coming back to the initial question about the 2°C objective and the ambiguity of its interpretation, we have first to underline that the 2°C value is here purely illustrative. Those who think that it is allready too late to avoid a huge overshoot of this ceiling could argue that 2.5 or 3°C could have been more relevant. However, this does not invalidate the three following conclusions:

1. Extremely low discount rates or overly optimistic views about mitigation costs are not a precondition for ambitious action;

2. This statement holds even in the absence of catastrophic climate change in the Weitzmann sense;

3. The shape of the damage curve matters as much as the absolute level of action in the cost-benefit balance of climate policies (Dumas and Ha-Duong, 2008).

Beyond, if we now assume a delay in action, two mechanisms enter into play: first, the number of pro-2°C worldviews (panglossians and almost zero

PTP excluded) falls by 44% for a 20 years delay; second, the number and magnitude of the overshooting increases. But the number of the believers in the linearity of damage decreases far less; again this is due to the fact that for them, damage occurs very late even in the case of a large delay in acting.

Appendix

A The model

We built an IAM which couples a macroeconomic optimal growth model with a climatic one. Here we present the very basic equations of the model and the main analytical results.

Let's recall that the benevolent social planner have to maximize the following objective:

$$\sum_{s,j=1}^{S} p_s q_j \sum_{t=0}^{T-1} N_t \Gamma^t u\left(\frac{C_t^{s,j}}{N_t}\right),$$

under four constraints: $\forall s$ and $\forall j$,

- capital dynamics (as presented above):

  $$K_{t+1}^{s,j} = (1-\delta)K_t^{s,j} + (Y(K_t^{s,j}, L_t) - C_t^{s,j} - C_a(a_t^{s,j}, a_{t-1}^{s,j}, K_t^{s,j}) - D^j(\theta_{t,at}^{s,j}, K_t^{s,j})),$$

  with,

  $$D^j(\theta_t^{s,j}, K_t^{s,j}) = \left[\alpha(\theta_t^{s,j}) + \left(\frac{d}{1+((2-e)/e)^{2(Z^j-\theta_t^{s,j})/\eta}}\right)\right] Y(K_t^{s,j}, L_t),$$

  and,

  $$C_a(a_t^{s,j}, a_{t-1}^{s,j}, K_t^{s,j}) = PT_t\left(a_t^{s,j}\zeta + (BK-\zeta)\frac{(a_t^{s,j})^\nu}{\nu} + \xi^2(a_t^{s,j} - a_{t-1}^{s,j})^2\right) E_t^{s,j},$$

  with the following equation of emissions (before abatement):

  $$E_t^{s,j} = \sigma_t Y(K_t^{s,j}, L_t);$$

- carbon dynamics as a three-reservoir linear carbon-cycle model: We use the C-Cycle of Nordhaus (Nordhaus and Boyer, 1999), a linear three-reservoir model (atmosphere, biosphere + surface ocean and deep ocean). Each reservoir is assumed to be homogeneous (well mixed in the short run) and is characterized by a residence time inside the box and corresponding mixing rates with the two other reservoirs (longer timescales). Carbon flows between reservoirs depend on constant transfert coefficients. GHGs emissions (CO_2 solely) accumulate in the atmosphere and they are slowly removed by biospheric and oceanic sinks.

The dynamics of carbon flows is given by:

$$\begin{pmatrix} A_{t+1}^{s,j} \\ B_{t+1}^{s,j} \\ O_{t+1}^{s,j} \end{pmatrix} = \mathbf{C}_{trans} \begin{pmatrix} A_{t}^{s,j} \\ B_{t}^{s,j} \\ O_{t}^{s,j} \end{pmatrix} + (1 - a_t^{s,j}) E_t^{s,j} \mathbf{v}, \tag{1}$$

where $A_t^{s,j}$ represents the carbon contents of atmosphere at time t, $B_t^{s,j}$, the contents of upper ocean and biosphere at time t, $O_t^{s,j}$, the carbon contents of deep ocean at time t. Notice that before t_{info}, carbon contents of each reservoir are set and written as follows $\overline{A}_t$, $\overline{B}_t$, $\overline{O}_t$. $\mathbf{C}_{trans}$ is the net transfer coefficients matrix and $\mathbf{v}$ is a column vector (1,0,0). Nordhaus calibration on existing carbon-cycle models gives the following results (for a decadal time step):

$$C_{trans} = \begin{pmatrix} c_{11} & c_{12} & 0 \\ c_{21} & c_{22} & c_{23} \\ 0 & c_{32} & c_{33} \end{pmatrix} = \begin{pmatrix} 0.66616 & 0.27607 & 0 \\ 0.33384 & 0.60897 & 0.00422 \\ 0 & 0.11496 & 0.99578 \end{pmatrix}$$

The main criticism which may be address to this C-cycle model is that the transfer coefficients are constant. In particular, they do not depend on the carbon contentof the reservoir (e.g. deforestation hindering biospheric sinks (Gitz and Ciais, 2003)) nor are they influenced by ongoing climatic change (e.g. positive feedbacks between climate change and carbon cycle).

- temperatures dynamics as a reduced-form climate model: This model is very close to Schneider and Thompson's two-box model (Schneider and Thompson, 1981). A set of two equations is used to describe global mean temperature variation (3) since pre-industrial times in response to additional human-induced forcing (2). More precisely, the model describes the modification of the thermal equilibrium between atmosphere and surface ocean in response to anthropogenic greenhouse effect.

  The radiative forcing equation is given by:

$$F_t(A_t^{s,j}) = F_{2x} \frac{\log(A_t^{s,j}/A_{PI})}{\log 2}, \tag{2}$$

where F_t is the radiative forcing at time t (W.m^{-2}), F_{2x}, the instantaneous radiative forcing for a doubling of preindustrial concentration, set at 3.71 W.m^{-2} and A_{PI}, the atmospheric concentration at preindustrial times, set at 280 ppm.

The temperature increase equation is given by:

$$\begin{pmatrix} \theta^{s,j}_{t,at} \\ \theta^{s,j}_{t,oc} \end{pmatrix} = \begin{pmatrix} \sigma_1(-\frac{F_{2x}}{T^s_{2x}}\theta^{s,j}_{t,at} - \sigma_2\phi^{s,j}_T + F_t(A^{s,j}_t)) \\ \sigma_3\phi^{s,j}_T \end{pmatrix}, \tag{3}$$

where $\theta^{s,j}_{t,at}$ and $\theta^{s,j}_{t,oc}$ are respectively global mean atmospheric and oceanic temperature rises from pre-industrial times (°C), $\phi^{s,j}_T$ is the difference between $\theta^{s,j}_{t,at}$ and $\theta^{s,j}_{t,oc}$ ($\phi^{s,j}_T = \theta^{s,j}_{t,at} - \theta^{s,j}_{t,oc}$), σ_1, σ_2, σ_3 are transfert coefficients, and T^s_{2x} is the climate sensitivity.

- abatement constraint is:

$$0 \le a^{s,j}_t \le 1.$$

We note

$$\mu^{s,j}_t = u'\left(\frac{C^{s,j}_{t-1}}{N_{t-1}}\right)\frac{1}{1+\rho}$$

and $\gamma^{s,j}_t = p_s q_j \mu^{s,j}_t$. $\lambda_{t,at}$ is the langrange multiplier corresponding with the atmospheric concentrations, linked with marginal damage through a set of equations (not shown) determining the lagrangian multipliers associated with the dynamics of carbon cycle and temperature. $E[X]$ is the expected value of X over s and j. First order conditions of the centralized model lead to the social discount rates (SDR_t).

$\forall t \le t_i$:

$$\begin{aligned} SDR_t &= (1+\rho)\frac{E\left[u'\left(\frac{C^{s,j}_{t-1}}{N_{t-1}}\right)\right]}{E\left[u'\left(\frac{C^{s,j}_{t}}{N_{t}}\right)\right]} - 1 \\ &= Y'(\overline{K}_t, L_t)\left(1 - \left(\frac{\lambda_{at,t}(1-\overline{a}_t)}{E[\mu_t]} + c_M(\overline{a}_t, \overline{a}_{t-1})\right)\sigma_t - \frac{E[\mu_t d_M(\theta_{at,t})]}{E[\mu_t]}\right) - \delta, \end{aligned}$$

with c_M, the mean cost of abatement:

$$c_M(a_t, a_{t-1}) = PT_t.\left(a_t\zeta + (BK-\zeta)\frac{(a_t)^\nu}{\nu} + \frac{Y_0}{E_0}\xi^2(a_t - a_{t-1})^2\right),$$

and d_M, mean damage:

$$d^j_M(\theta_t) = \alpha\theta_t + \left(\frac{d}{1+((2-e)/e)^{2(Z^j-\theta_t)/\eta}}\right);$$

At $t_i + 1$:

$$SDR_{t_i+1} = -\delta + Y'(\overline{K}_{t_i+1}, L_{t_i+1})$$
$$\left(1 - \frac{\left(\sum_{s,j=1}^{S} (\lambda^{s,j}_{at,t_i+1}(1 - a^{s,j}_{t_i+1}) + p^s q^j \mu^{s,j}_{t_i+1} c_M(a^{s,j}_{t_i+1}, \overline{a}_{t_i}))\sigma_{t_i+1}\right) + E[\mu_{t_i+1} d_M(\theta_{at,t})]}{E[\mu_{t_i+1}]}\right).$$

$\forall j$ and $\forall s$ and $\forall t > t_i + 2$

$$SDR_t = Y'(K^{s,j}_t, L_t)\left(1 - \left[\left(\frac{\lambda^{s,j}_{at,t}(1 - a^{s,j}_t)}{\gamma^{s,j}_t} + c_M(a^{s,j}_t, a^{s,j}_{t-1})\right)\sigma_t + d^j_M(\theta^{s,j}_t)\right]\right) - \delta.$$

A.1 Decentralization of the optimum

Companies' objective

Companies aim at maximizing their discounted intertemporal profit. We note their program as:

$$\begin{aligned}
\max_{K,a} \pi \quad = \quad & \sum_{s,j=1}^{S} p_s q_j \sum_{t=0}^{t_i} \left(\prod_{t=0}^{t_i} \frac{1}{(1+\overline{r}_t)}\right) \big(Y(\overline{K}_t, L_t) - C_a(\overline{a}_t, \overline{a}_{t-1}, \overline{K}_t) - \overline{r}_t \overline{K}_t - \delta \overline{K}_t \\
& -w_t L_t - \omega_t (1 - \overline{a}_t)\sigma_t Y(\overline{K}_t, L_t)\big) \\
& + \sum_{s,j=1}^{S} p_s q_j \left(\overline{\Pi} \frac{1}{(1 + r^{s,j}_{t_i+1})}\right) \big(Y(\overline{K}_{t_i+1}, L_{t_i+1}) - C_a(a^{s,j}_{t_i+1}, \overline{a}_{t_i}, \overline{K}_{t_i+1}) \\
& -r^{s,j}_{t_i+1} \overline{K}_{t_i+1} - \delta \overline{K}_{t_i+1} - w_{t_i+1} L_{t_i+1} - \omega^{s,j}_{t_i+1}(1 - a^{s,j}_{t_i+1})\sigma_{t_i+1} Y(\overline{K}_{t_i+1}, L_{t_i+1})\big) \\
& + \sum_{s,j=1}^{S} p_s q_j \sum_{t=t_i+2}^{T-1} \left(\overline{\Pi} \prod_{t=t_i+1}^{T-1} \frac{1}{(1 + r^{s,j}_t)}\right) \big(Y(K^{s,j}_t, L_t) - C_a(a^{s,j}_t, a^{s,j}_{t-1}, K^{s,j}_t) \\
& -r^{s,j}_t K^{s,j}_t - \delta K^{s,j}_t - w_t L_t - \omega^{s,j}_t (1 - a^{s,j}_t)\sigma_t Y(K^{s,j}_t, L_t)\big)
\end{aligned}$$

with $\overline{\Pi} = \prod_{t=0}^{t_i} \frac{1}{(1+\overline{r}_t)}$, $\omega^{s,j}_t$ the optimal tax put on carbon emissions which is identified, at the optimum, as the SCC, and r_t, the interest rate (or marginal productivity of capital) which is determined endogenously in order to capture the impacts of climate change.

First order conditions to recover the optimal rate of tax and so the SCC

Numerical calculations of the SCC are based upon the following formula.

$\forall t < t_i + 1$ we obtain:

$$\begin{aligned}
\frac{\partial \pi_t}{\partial \overline{a}_t} &= 0 \quad \Rightarrow \quad \omega_t = \frac{C'_{a_1}(\overline{a}_t, \overline{a}_{t-1}, \overline{K}_t) + \frac{1}{1+\overline{r}_{t+1}} C'_{a_2}(\overline{a}_{t+1}, \overline{a}_t, \overline{K}_{t+1})}{\sigma_t Y(\overline{K}_t, L_t)} \\
\frac{\partial \pi}{\partial \overline{K}_t} &= 0 \quad \Rightarrow \quad \overline{r}_t = Y'(\overline{K}_t, L_t)\left(1 - (\omega_t(1-\overline{a}_t) + c_M(\overline{a}_t, \overline{a}_{t-1}))\sigma_t\right) - \delta
\end{aligned}$$

At $t_i + 1$, $\forall s$ and $\forall j$:

$$\begin{aligned}
\omega^{s,j}_{t_i+1} &= \frac{\left(\sum_{s,j=1}^{S} p_s q_j C'_{a_1}(a^{s,j}_{t_i+1}, \overline{a}_{t_i}, \overline{K}_{t_i+1})\right) + \frac{1}{1+r^{s,j}_{t_i+2}} C'_{a_2}(a^{s,j}_{t_i+2}, a^{s,j}_{t_i+1}, K^{s,j}_{t_i+2})}{\sigma_{t_i+1} Y(\overline{K}_{t_i+1}, L_{t_i+1})} \\
\overline{r}_{t_i+1} &= Y'(\overline{K}_{t_i+1}, L_{t_i+1})\left(1 - \sum_{s,j=1}^{S} p_s q_j \left[(\omega^{s,j}_{t_i+1}(1 - a^{s,j}_{t_i+1}) + c_M(a^{s,j}_{t_i+1}, \overline{a}_{t_i}))\sigma_{t_i+1}\right]\right) - \delta.
\end{aligned}$$

$\forall t > t_i + 1$, $\forall j$ and $\forall s$ we have:

$$\begin{aligned}
\frac{\partial \pi}{\partial a^{s,j}_t} &= 0 \quad \Rightarrow \quad \omega^{s,j}_t = \frac{C'_{a_1}(a^{s,j}_t, a^{s,j}_{t-1}, K^{s,j}_t) + \frac{1}{1+r_{t+1}} C'_{a_2}(a^{s,j}_{t+1}, a^{s,j}_t, K^{s,j}_{t+1})}{\sigma_t Y(K^{s,j}_t, L_t)} \\
\frac{\partial \pi}{\partial K^{s,j}_t} &= 0 \quad \Rightarrow \quad r_t = Y'(K^{s,j}_t, L_t)\left(1 - (\omega^{s,j}_t(1 - a^{s,j}_t) + c_M(a^{s,j}_t, a^{s,j}_{t-1}))\sigma_t\right) - \delta.
\end{aligned}$$

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